A New Topological Optimization Method for the Mechanical and Control-Oriented Design of Compliant Piezoelectric Devices

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1. Abstract

This paper presents a new method developed for the optimal design of piezoactive compliant mechanisms. It is based on a flexible building blocks method, called FlexIn, which uses an evolutionary approach, to optimize a truss-like structure made of passive and active piezoelectric building blocks. An electromechanical approach, based on a mixed finite element method, is used to establish the model of the piezoelectric blocks. A planar monolithic compliant micro-actuator is synthesized by the optimization method, based on the specifications drawn from both mechanical and innovative control-oriented considerations. In particular, these last criteria have been drawn here to optimize modal controllability and observability of the system, which is particularly interesting when considering identification and control of flexible structures.

2. Keywords: Piezoactuator design, compliant mechanisms, microgripper, control-oriented design, topology optimization.

3. Introduction

In microrobotic applications, one type of smart material-based actuator typically used to actuate compliant structures is piezoceramic PZT actuators: when compared to other conventional actuation principles at small scales, they have very appealing properties in the sense of micromechatronic design. Piezoelectric actuation is mostly used for microrobot design in order to achieve nanometric resolutions, and has naturally became widespread in micromanipulation systems [1].

However, one limitation of piezoelectric actuators is that they are capable of producing only about 0.1% strain, resulting in a restricted range of motion. A number of papers address the problem of optimally designing coupling compliant structures to act as stroke amplifiers of the piezoelectric actuator [2], [3], [4]. Few studies consider the topology optimization (shape) of monolithic PZT active structures [5]. But, previous works in topology design of active compliant structures have mainly focused on quasi-static applications, which may be sub-optimal in dynamic operations, or, worse, may induce degraded functioning. Very few related works deal with topological optimization method including frequency response analysis [6], [7]. There, the objective functions generally use the maximization of either geometrical advantage (stroke amplification), or mechanical advantage (force amplification), only in the restrictive case of predetermined harmonic loadings.

To improve such active compliant micromechanisms performances, it can be useful to optimize them from the first designing step, taking into account versatile microrobotic criteria [8]. A global systematic design approach is presented in this paper, where topology optimization of the piezoactive structure, as well as that of its frequency response, is used to design compliant smart mechanisms. This method is based on the flexible building block method called FlexIn ("Flexible Innovation"). It considers a planar compliant mechanism as an assembly of both passive and piezoactive compliant building blocks, and uses a multi-objective genetic algorithm to optimize these structures. To complete the panel of purely mechanical criteria, innovative control-based metrics have been newly proposed in FlexIn. These criteria are useful tools to ensure the efficient control of the flexible structures afterwards.

This paper is organized as follows: firstly, we will briefly review the underlying idea of the FlexIn methodology for the optimal design of smart compliant mechanisms. In particular, the electromechanical finite element approach for the model of the piezoactive building blocks, the state model approach used in

FlexIn are presented. Then, a topology design strategy is drawn to take into account, in the optimization algorithm, accurate model-reduction and control of flexible structures. Two resulting numerical criteria will help meeting open-loop input-output transfer performances with specific operation requirements. Finally, FlexIn tool is used to optimally synthesize a compliant piezoactuator.

4. FlexIn: a compliant mechanisms stochastic design methodology

In this section, we briefly present the flexible building blocks method, which has been implemented for the optimal design of micromechanical planar mechanisms in a software called FlexIn (developed with MATLAB) [9], [10], [11]. It uses a multi-objective evolutionary algorithm approach for the optimal design of smart compliant mechanisms made of an assembly of elementary passive and active compliant building blocks.

4.1. Compliant building blocks

Two libraries of compliant elements in limited number are proposed in FlexIn. These bases are composed respectively of 36 and 19 elements of passive and piezoactive blocks, made of beams assembly (figure 1). They are sufficient to build a high variety of topologies. In particular, the various topologies of piezoactive blocks allow them to furnish multiple coupled degrees of freedom, thus generating more complex movements with only one building block.

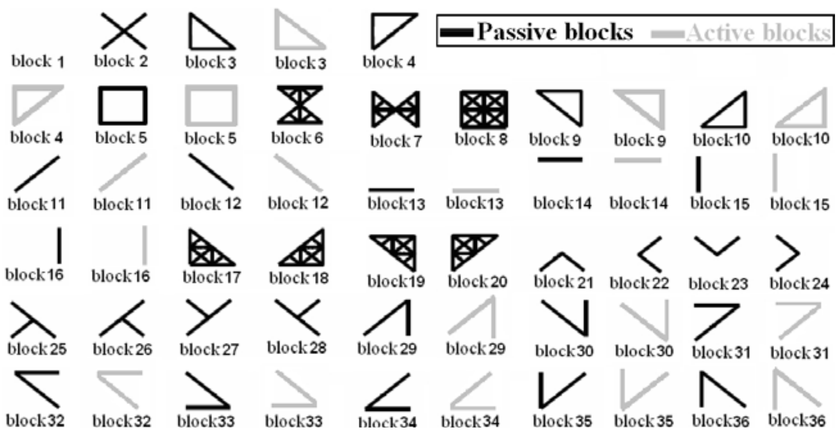

Figure 1: Passive (black) and piezoactive (grey) libraries of compliant building blocks, for planar compliant mechanisms synthesis using FlexIn.

4.2. Principle of the method and design parameters

The specification of a planar compliant mechanism problem considers specific boundary conditions: fixed frame location, input (actuators), contacts and output (end-effector). Different types of actuation principles can be used: either external or internal force/displacement actuators defined at particular nodes of the mesh [10], or integrated piezoactive elements taken from the active library [11]. The design method consists in searching for an optimal distribution of allowed building blocks, as well as for the optimal set of structural parameters and materials. The location of fixed nodes and that of the actuators and/or piezoactive blocks can also be considered as optimisation parameters. The topology optimization method, inspired from [12], uses a genetic algorithm approach, which allows true multicriteria optimization and the use of these discrete variables (figure 2). The algorithm is structured as follows:

- Discrete variable parametrization of compliant mechanisms considering conception requirements (mesh size, topology, material and thickness, boundary conditions),
- Evaluation of individuals (design criteria calculation),
- Stochastic operators for the optimization (modification of compliant mechanisms description).

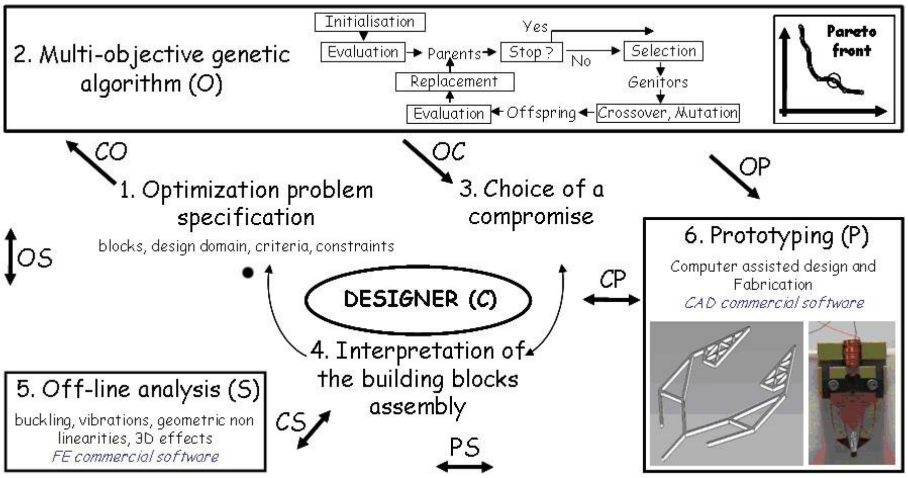

Figure 2: Flowchart of the FlexIn optimal design method of compliant structures (multicriteria optimization).

4.3. Multi criteria genetic algorithm

Many fitness functions are available in FlexIn, thus allowing the optimal design of devices within a wide schedule of conditions:

- several static mechanical fitness (free displacement and blocking force at the output port, geometric advantage, mechanical advantage, etc.)
- various dynamic control-oriented metrics have been newly implemented in FlexIn to meet specific control requirements for microrobotics devices. Obviously, the design strategy depends on the metrics chosen, which must be based on the real needs for the device use.

Multi-degrees of freedom mechanisms design can also be considered. The optimization algorithm generates a set of pseudo-optimal solutions (see 2 in figure 2) in the case of multicriteria optimization problem (and obviously only one optimal solution for monocriterion optimization). The designer can choose, interpret and analyse the obtained structures that best suit his design problem (see 3 to 5 in figure 2).

4.4. Electro-mechanical FE model of the elementary piezoelectric building blocks

In FlexIn, it is assumed that the compliant mechanisms are undergoing structural deformations, mainly due to the bending of the beams constituting the blocks. Thus, the models of the blocks are obtained considering Navier-Bernoulli beam type finite elements. Structural parameters of each rectangular block are height, width and thickness. Material characteristics of each block are parameterized by Young's modulus, Poisson's ratio, yield strength, density, and piezoelectric coefficients for the piezoactive blocks. To allow the calculation of different criteria, FlexIn uses the FE model of each block of the libraries. To obtain the FE formulation of the piezoelectric blocks, a model of a piezoelectric beam is first needed.

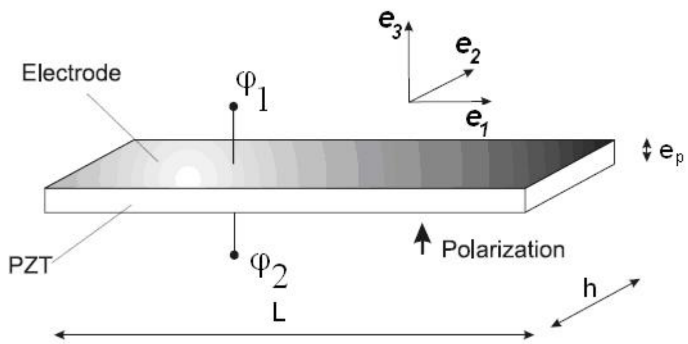

Figure 3: Thickness-polarized piezoelectric beam transducer with electroded surfaces, and orientation in the material reference frame $(\mathbf{e_1}, \mathbf{e_2}, \mathbf{e_3})$. φ_1 and φ_2 denotes the electric potential of the electrodes.

We consider that the piezoceramic beams constituting the active blocks are perfectly bonded to electrodes at their lower and upper faces (figure 3). Exploiting the transverse effect of piezoelectricity, longitudinal deformation S_{11} along L dimension is generated under the transverse electric field E_3. Considering the one-dimensional form of piezoelectricity equation along the length direction of the beam, the piezoelectric coupling matrix $\mathbf{d}$ and the stress-free electric permittivity matrix ε^t are each represented by a single coefficient, d_{31} and ε_{33} respectively, and the electric-free compliance matrix $\mathbf{s}^E$ is represented by s_{11}^E. The subscript "t" denotes the transpose of a matrix. Hence, within the piezoelectric beam, the constitutive relations for the strain S_{11} and electric displacement D_3, as functions of stress T_{11} and electric field E_3, take the form:

$$\left\{ \begin{array}{c} S_{11} \\ D_3 \end{array} \right\} = \left[\begin{array}{cc} s_{11}^E & d_{31} \\ d_{31} & \varepsilon_{33}^T \end{array} \right] \left\{ \begin{array}{c} T_{11} \\ E_3 \end{array} \right\} \tag{1}$$

The superscripts "E" and "T" refer to values taken respectively at constant electric and stress fields.

The displacement field over a planar beam element is described from its longitudinal u, tangential v and rotational ω components at x_p curvilinear abscissa (figure 4), and is related to the corresponding node values $\eta_\mathbf{b} = (u_A, v_A, \omega_A, u_B, v_B, \omega_B)^t_{R_p}$ in the beam coordinate system $R_p = (A, \mathbf{x_p}, \mathbf{y_p}, \mathbf{z_p})$. From Hamilton's principle modified for general electromechanical system [13], the model of the active beam takes the following form:

$$\mathbf{M_b}\ddot{\eta}_\mathbf{b} + \mathbf{K_b}\eta_\mathbf{b} = \mathbf{G_b}\mathbf{\Phi_b} + \mathbf{Fr_b} \tag{2}$$

where $\mathbf{M_b}$, $\mathbf{K_b}$ and $\mathbf{G_b}$ are respectively the mass, stiffness and electromechanical coupling beam matrices. $\mathbf{\Phi_b} = [\varphi_\mathbf{1}\varphi_\mathbf{2}]^t$ is the vector representing the electric potentials on the upper and lower faces of the piezoelectric beam. Matrix $\mathbf{G_b}$ induces piezoelectric loads, which makes the actuator beam expand (or contract) proportionally to the external controlled potential difference $(\varphi_\mathbf{1} - \varphi_\mathbf{2})$. The forces vector $\mathbf{Fr_b}$, is due to the variational mechanical work terms, and is written $\mathbf{Fr_b} = \left(\mathbf{R^x_A}, \ \mathbf{R^y_A}, \ \mathbf{H^z_A}, \ \mathbf{R^x_B}, \ \mathbf{R^y_B}, \ \mathbf{H^z_B} \right)^t_{R_p}$ (figure 4). Displacement field is related to the corresponding node values $\eta_\mathbf{b}$ by the mean of the shape functions, calculated under Euler-Bernoulli beam assumptions. Detailed derivations can be readily found in finite element textbooks, and corresponding matrices in [11]. The stiffness, damping, and mass ma-

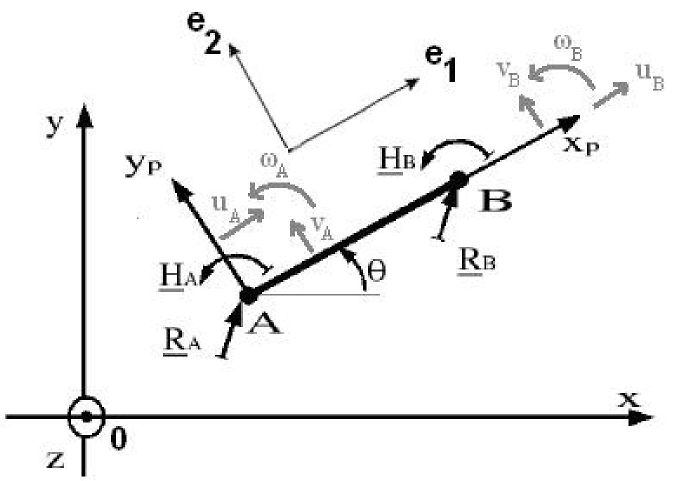

Figure 4: Curvilinear coordinates of the piezoelectric beam $A - B$, and its orientation in the global coordinate system $R' = (0, \mathbf{x}, \mathbf{y}, \mathbf{z})$. $\mathbf{R}$ and $\mathbf{H}$ represent the in-plane nodal force and moment at the beam extremities.

trices of each block are then calculated numerically, considering every combination of the discrete values allowed for the structural optimization variables. Then, they are condensed to reduce the numerical problem size, which is of great interest when using a genetic algorithm approach for multi-objective optimal design. The calculation of the different reduced matrices of each valued-block is done one time only at the beginning of the optimal design problem (before running the genetic algorithm), thus saving running time.

4.5. Electro-mechanical FE model of the FlexIn structure

The global dynamic behavior of a structure results from the mass, damping, stiffness and electromechanical coupling matrices assembly of the constitutive blocks, and is done at each step for each individual during the optimization process.

During the optimization, candidate structures are generated by the genetic algorithm. The conservative dynamic behavior of a structure is described through its mass $\mathbf{M_g}$, stiffness $\mathbf{K_g}$ and electromechanical coupling $\mathbf{G_g}$ matrices, obtained by the assembly in $R^{'}$ of the matrices of all the blocks constituting the structure. This assembly is done during the optimization process at each generation and for each individual.

Each flexible structure synthesized by FlexIn is defined as a finite-dimension, controllable and observable linear system with small damping and complex conjugate poles [14]. Its undamped dynamic behavior is modeled by the following second-order differential matrix equations:

$$\mathbf{M_g}\ddot{\eta}_\mathbf{g} + \mathbf{K_g}\eta_\mathbf{g} = \mathbf{E_g}\mathbf{u} \tag{3}$$

and

$$\mathbf{y} = \mathbf{F_g}\eta_\mathbf{g} \tag{4}$$

Let us consider in the following the integers p, s, and r, which denote the numbers of degrees of freedom (DOF) of the structure, inputs (i.e. actuators) and observed outputs (sensors), respectively. In (Eq.3), remind that $\eta_\mathbf{g}$ is the $p \times 1$ nodal displacement vector. $\mathbf{u}$ is the $s \times 1$ input vector which defines the controlled command of the actuator. For example, in case of a piezoelectric actuation scheme, $\mathbf{u}$ is defined by $\mathbf{\Phi_g}$. In that case, the $p \times s$ input matrix $\mathbf{E_g}$ is exactly $\mathbf{G_g}$. $\mathbf{y}$ is the $r \times 1$ output vector, defined from the $r \times p$ output displacement matrix $\mathbf{F_g}$. Each element of $\mathbf{u}$ (resp. $\mathbf{y}$) denotes a physical actuator (resp. sensor) whose related DOF is defined by the location of the nonzero entry in the corresponding column in $\mathbf{E_g}$ (resp. row in $\mathbf{F_g}$).

By means of modal decomposition, a solution of the form

$$\eta_\mathbf{g}(t) = \sum_{i=1}^{p} \mathbf{\Psi_i}\mathbf{q}(t) = \mathbf{\Psi}\mathbf{q}(t) \tag{5}$$

is considered, which consists of a linear combination of mode shapes $\mathbf{\Psi_i}$. $\mathbf{q}$ is the $p \times 1$ modal displacement vector. The eigenvectors matrix $\mathbf{\Psi} = \left[\begin{array}{ccc} \mathbf{\Psi_1} & \dots & \mathbf{\Psi_p} \end{array}\right]$ and corresponding eigenfrequencies ω_i are obtained as solutions of the free undamped vibration eigenproblem:

$$\left(\mathbf{K}_g - \omega_i^2 \mathbf{M}_g\right) \mathbf{\Psi}_i = 0. \tag{6}$$

because the damping has very little influence on the natural frequencies of flexible structures synthesized.

Replacing $\eta_\mathbf{g}$ by $\mathbf{\Psi q}$ in (Eq. 3), multiplying on the left by $\mathbf{\Psi}^t$, the induced orthogonality relationships in modal form lead to

$$\ddot{\mathbf{q}} + \mathbf{diag}\left(\omega_i^2\right)\mathbf{q} = \mathbf{\Psi}^t\mathbf{E_g}\mathbf{u} \tag{7}$$

and

$$\mathbf{y} = \mathbf{F_g}\mathbf{\Psi}\mathbf{q} \tag{8}$$

We can now introduce diagonal damping by using Basil's hypothesis, so that (Eq.7) becomes

$$\ddot{\mathbf{q}} + \mathbf{diag}(2\xi_i\omega_i)\dot{\mathbf{q}} + \mathbf{diag}(\omega_i^2)\mathbf{q} = \mathbf{\Psi}^t\mathbf{E_g}\mathbf{u} \tag{9}$$

where ξ_i is the i^{th} modal damping ratio. This hypothesis can be made because the system to control is slightly damped in the low-frequency band, where the modes are well separated.

4.6. Modal equation of motion of FlexIn structures

One interesting state vector $\mathbf{x}$, of dimension $2p \times 1$, consists of modal velocities and frequency weighted modal displacements:

$$\mathbf{x} = \left(\begin{array}{ccccc} \dot{q}_1 & \omega_1 q_1 & \dots & \dot{q}_p & \omega_p q_p \end{array}\right)^t \tag{10}$$

with the advantage that the elements of state vector corresponding to each mode are about the same magnitude. This yields the matrices triplet $(\mathbf{A}, \mathbf{B}, \mathbf{C})$ which denotes the modal state-space representation of a structure as stated below,

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{11}$$

$$\mathbf{y} = \mathbf{C}\mathbf{x}. \tag{12}$$

The matrices take the forms $\mathbf{A} = \mathbf{diag}\begin{pmatrix} \mathbf{A_1}, & \dots, & \mathbf{A_p} \end{pmatrix}$, $\mathbf{B} = \begin{pmatrix} \mathbf{B_1^t}, & \dots, & \mathbf{B_p^t} \end{pmatrix}^t$, and $\mathbf{C} = \begin{pmatrix} \mathbf{C_1}, & \dots, & \mathbf{C_p} \end{pmatrix}$, with, for $i = 1, ..., p$,

$$\mathbf{A_i} = \begin{bmatrix} -2\zeta_i\omega_i & -\omega_i \\ \omega_i & 0 \end{bmatrix}, \tag{13}$$

$$\mathbf{B_i} = \begin{bmatrix} \mathbf{b_i} \\ \mathbf{0} \end{bmatrix}, \tag{14}$$

$$\mathbf{C_i} = \begin{bmatrix} \mathbf{0} & \frac{\mathbf{c_i}}{\omega_i} \end{bmatrix}, \tag{15}$$

where $\mathbf{b_i} = \mathbf{\Psi_i^t E_g}$ is $1 \times s$ size, and $\mathbf{c_i} = \mathbf{F_g \Psi_i}$ is $r \times 1$ size. $\mathbf{b_i}$ and $\mathbf{c_i}$ are the i^{th} row of $\mathbf{\Psi}^t\mathbf{E_g}$ and the i^{th} column of $\mathbf{F_g}\Psi$ respectively. It is important to note that $\mathbf{A}$ matrix depends on the structure itself (eigenfrequencies and modal damping ratios), $\mathbf{B}$ matrix on the location and class of actuators, and $\mathbf{C}$ matrix on location and class of sensors. This modal state is considered to be a physical coordinate because of its direct physical link to structural mode shapes.

5. New criteria for fitting the input-output frequency response of flexible systems

From the computation of the linear state model of compliant systems, an optimal topology design strategy is derived taking into account control considerations. New FlexIn numerical criteria help reaching input-output open-loop system performances with specific operation requirements.

5.1. Evaluation of the model reduction cost

Since the dynamic model of a flexible structure is characterized by a large number of resonant modes, accurate identification of all the dominant system dynamics often leads to very high order model. Thus, a model reduction is required.

In FlexIn, a first criterion has been drawn to optimize the reduced-model accuracy of the systems, while limiting spillover effects (figure 5). Given a set of structures to optimize, the optimal structures are chosen as the ones guaranteeing the highest joint controllability and observability for all the modes in the bandwidth of interest (i.e. resonance peaks amplitudes must be maximized in the frequencies bandwidth $[0, \omega_c]$ to increase authority control on these dominant modes), while providing the minimum joint controllability and observability of the neglected modes (i.e. the amplitudes of resonance peaks after cut-off frequency must be minimized to increase gain margin and to limit modes destabilization in this area). This criterion will enable the rise of structures with accurate reduced model, based on a few highly dominant modes, allowing the easy identification and computation of state model, well adapted to further design and implementation of the control system.

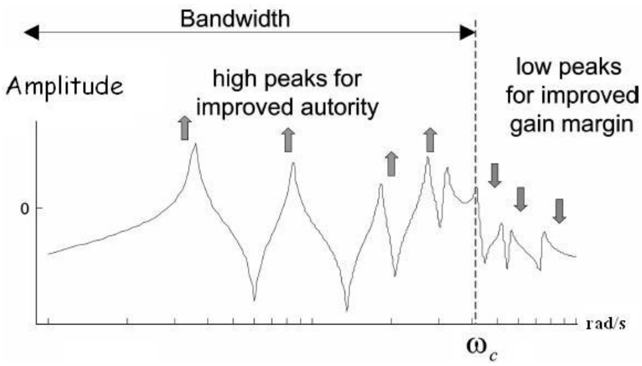

Figure 5: Desired form of the open-loop FRF.

$\|.\|_\infty$ norm characterizes the maximal amplification of the input signal energy that the system can produce. In $SISO$ system case, it simply represents the maximum amplitude value of the frequency response, formulated as follows for small damping system,

$$\|G_i\|_\infty \simeq \frac{|c_i b_i|}{2\xi_i\omega_i^2} \tag{16}$$

so that, according to [15], it can be almost proportionally linked to the corresponding σ_i Hankel Singular Value (HSV) of G_i as follows:

$$\|G_i\|_\infty \simeq 2\sigma_i \tag{17}$$

where

$$\sigma_i = \frac{\sqrt{\mathbf{c_i^t c_i b_i b_i^t}}}{4\xi_i \omega_i^2} \tag{18}$$

Thus, the k first resonant modes (where $k < p$) will be optimized to guarantee high HSV compared to the ones out of the bandwidth. The modal states with small HSV are both weakly controllable and weakly observable, and will be removed from the reduced-system.

As a consequence, the resulting dominant reduced-order model G_r defined as

$$G_r(j\omega) = \sum_{i=1}^{k} G_i(j\omega) \tag{19}$$

will match the full model $G(j\omega)$ with an accuracy related to the size of the HSV which were discarded [15].

To improve simultaneously the control authority on the k first dominant modes and the accuracy of the reduced order model, the first new criteria implemented in FlexIn is the following:

$$J_1^k = \frac{\sum\limits_{i=1}^{k} \sigma_i}{\sum\limits_{i=k+1}^{p} \sigma_i} \tag{20}$$

where the HSV are defined in their modal form for flexible structures. In our case study, an order $k = 2$ is chosen as a good compromise for the piezoelectric flexible structure model afterwards.

5.2. Minimum-phase properties for collocated behavior

There are a number of difficulties associated with the control of flexible structures (amongst them, variable resonance frequencies and highly resonant dynamics). One major characteristic of a collocated system is the interlacing of poles and zeros along the imaginary axis. For a lightly damped structure, poles and zeros are located in the left half-part in the pole-zero map. Such systems are minimum of phase, so that collocated systems are known to possess interesting properties. Vibration control of flexible structures involving collocated characteristics was discussed in [16]. Control was shown to have simple stability criteria due to the alternating poles and zeros pattern.

In FlexIn, an evaluation function was implemented to be used in the optimization process in order to obtain systems designs with collocated type open-loop transfer function, forcing the resonances (poles) and antiresonances (zeros) alternating in the reduced model. Inspired by [16], it can be shown that the maximization of the following discrete criterion will imply the interlacing pole-zero pattern exhibited by a collocated transfer function:

$$J_2^k = \left| \sum_{i=1}^{k} sign(c_i b_i) \right| \tag{21}$$

where $sign(.) = +1, 0, -1$, according to the argument sign. The sum over i concerns all the modes contained in the frequency spectrum of the first k dominant modes, where the alternative is desired. This criteria will force the static gains of G_i in the spectrum of interest to have the same sign. (In our application case k is set to 2, and only two numerical values are possible: the maximum value is $J_2^2 = 2$, otherwise $J_2^2 = 0$.)

6. Example of the optimal synthesis of a monolithic compliant piezoactuator

The concepts presented previously have been applied to the design of a microgripper actuator, considering a multi-criteria optimization problem, with both static mechanical (free stroke δ_x and blocking force F_x at the output node of the structure) and control-oriented J_1^2 and J_2^2 fitnesses.

6.1. Optimization problem specifications

We consider the synthesis of a symmetric monolithic microactuation mechanism, made of a single piezoelectric material PIC151 from PI Piezo Ceramic Technology [17]. Let us note that, since damping cannot be accurately known a priori before an identification procedure, modal damping is taken constant in the optimization algorithm, and equal to 1% for all resonant modes. At the end, the whole microactuator will be machined using Laser cutting technology into an electroded piezoelectric plate whose dimensions are $20mm \times 20mm$ with a thickness of $e_p = 200\mu m$. Electrodes are deposited on the whole upper and lower surfaces. To take advantage of the maximum size allowed for the piezoactive structure, the half microactuator topology is considered to have a maximal size of $15mm \times 9mm$, and a constant thickness of $200\mu m$.

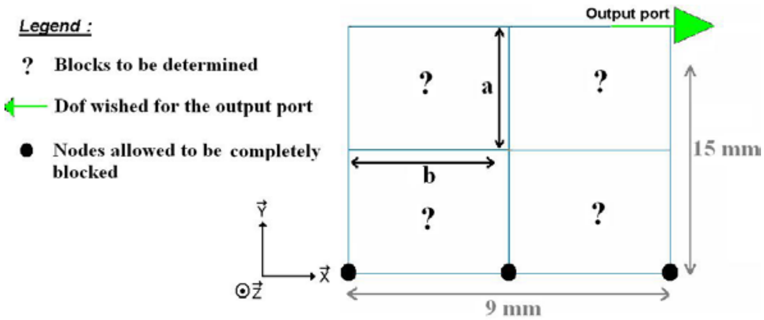

Figure 6: Mesh of the left-part of the symmetric PZT compliant micro-actuator with imposed and permitted boundary conditions. a and b optimization parameters define the relative height and width of the blocks.

The half-microactuator topology is defined to be made of either passive or active blocks inside a 2×2 mesh (figure 6). For the optimal synthesis run, the number of active blocks in the half-part will be allowed to vary between 1 and 4. When external voltages are applied to the blocks electrodes, the output node of the structure has to move along the x-axis and to produce a gripping force. For evaluation of static mechanical criteria, the potential difference between upper and lower face is taken equal to $200V$. The size ratio of the blocks can vary as $b_{\max}/b_{\min} \in [\![1;2]\!]$ and $a_{\max}/a_{\min} \in [\![1;2]\!]$ (figure 7). The number of blocked nodes is comprised between 1 and 3 among the locations permitted which are reported on figure 6.

6.2. Optimization results

FlexIn method can generate efficient piezoelectric actuated flexible mechanisms for microgripper devices. The best compromise structures are kept, when the genetic algorithm does not find any new pseudo-optimum during 130 subsequent generations. The set of pseudo-optimal solutions can be represented on Pareto fronts, giving their different fitness performances along each other (figure 7). The designer can choose among these solutions.

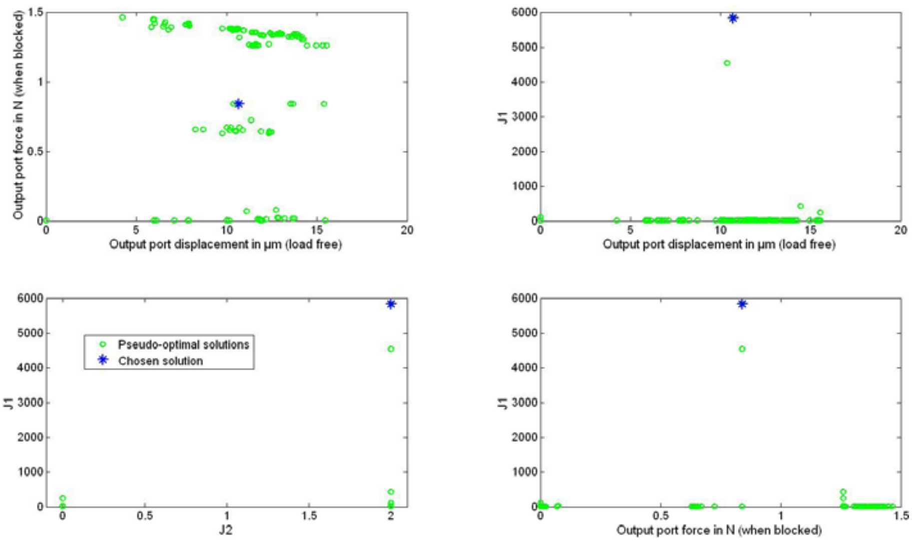

Figure 7: Pareto fronts of compliant mechanisms synthesized using FlexIn (genetic parameters used: population of 100 individuals, mutation probability of 45% on genes and 60% on individuals), and chosen pseudo-optimal solution.

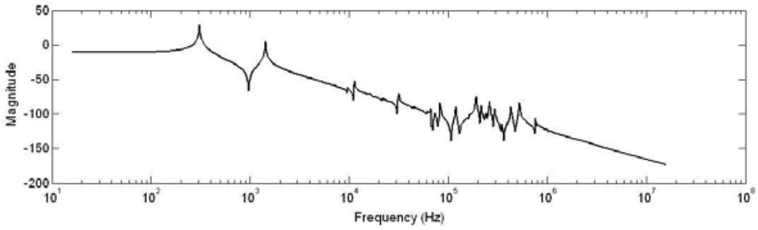

Figure 8: Bode amplitude diagram of the chosen solution between input (voltage u, in V) and output (deflexion δ_x, in μm) simulated by FlexIn.

From these fronts, one pseudo-optimal solution, whose whole topology is presented on figure 8, is chosen to illustrate performances: . $\delta_x = 10.69\mu m$, $F_x = 0.84N$, $J_1^2 = 5842.35$, $J_2^2 = 2$.

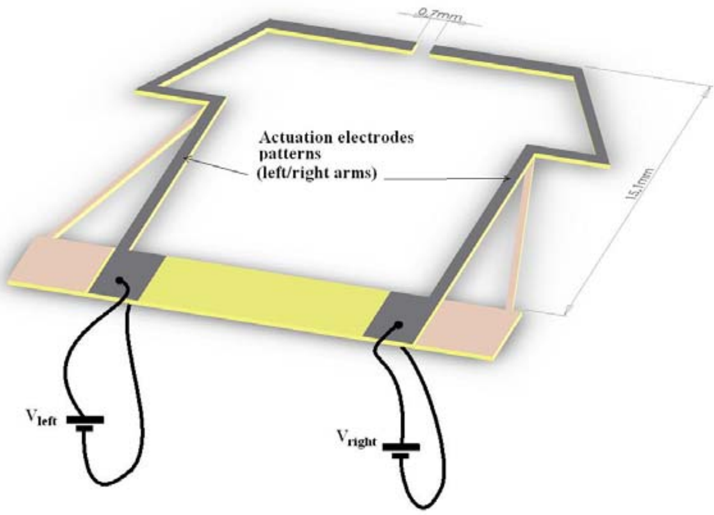

Figure 9: $3D$ CAD model of the piezoeletric device with top face electrode patterns. V_{left} (resp. V_{right}) is the controlled input for actuating the left (resp. right) arm.

This structure exhibits good quasi-static performances (high stroke δ_x and blocking force F_x values). Moreover, this solution is an example of structure with both good J_1^2 and J_2^2 control-oriented criteria (figure 10). It presents a good J_1^2 criterion performance: the authority control on the two first resonant modes is well optimized, resulting in an important roll-off after the second resonance. As expected with $J_2^2 = 2$, this structure exhibits an alternating pole/zero pattern in the spectrum of interest.

7. Conclusions

A new concept of optimal design method for smart compliant mechanisms has been presented. This method, called FlexIn, can consider a smart compliant mechanism as an assembly of passive and active compliant building blocks made of PZT, so that actuators are really integrated in the structure.

Complex multi-objective design problems can be solved by FlexIn, taking advantage of versatile criteria to synthesize high performance microrobotic flexible mechanisms designs. In addition to classical mechanical criteria, currently encountered in topology optimization (i.e. force and displacement maximization), FlexIn considers now simultaneously efficient control-based criteria.

Open-loop transfer considerations lead to two new efficient numerical criteria. A first criterion can modulate resonances amplitudes of its frequency response function in a spectrum of interest. A second criterion can force minimum-phase system property. These two criteria, coupled with mechanical ones, help designing non-intuitive compliant mechanisms.

This optimization strategy was tested for the optimal design of a microgripper actuator. The results obtained have proved that the method can furnish innovative and efficient solutions.

Future research includes optimal combination of sensors and actuators into the structure. A perspective is to take advantage of the direct piezoelectric effect, to consider as well force sensor integration inside monolithic piezoelectric structures to synthesize smart devices.

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